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Developing luminescence dating for extraterrestrial applications: Characterization of martian simulants and minerals

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Abstract

Currently, the timing of geologic and climatic events on Mars is poorly constrained, particularly for events that may have occurred over the last one million years of martian history, as the only dating technique currently available is crater counting which has an error of approximately one million years. Optically stimulated luminescence (OSL) dating has been suggested as a technique that can be adapted for robotic in situ dating of martian sediments that have been transported and deposited by wind or water over the last 10^4–10^5 years. This paper evaluates the potential of OSL for dating of martian surface geomorphologic features using a so-called "single-aliquot regenerative-dose" (SAR) technique for radiation dosimetry. The study evaluates the utility of the SAR technique for martian dating purposes using martian regolith simulants and martian meteorites. It is found that these materials have the requisite OSL properties for radiation dosimetry and can potentially be used for geological dating.

Keywords: OSL; Dating; Mars

1. Introduction

Understanding the geologic and climatic history of Mars is one of the primary goals of planetary exploration and the scientific community. Detailed studies of images of the martian surface indicate that Mars has been subject to feature-forming aeolian activity (Albee, 2003; Greeley, 1992) that is ongoing (Armstrong and Leovy, 2005; Edgett and Malin, 2000), and recent evidence from the Opportunity landing site has intensified the debate about the role of water in shaping the martian environment (Herkenhoff et al., 2004; Knauth et al., 2005). In addition to the debate about the presence or absence of such processes, the time periods over which they may have been active are also important. Currently, no chronometric dating methods are yet available for the study of the geologic and climatic history of the planet (Clifford et al., 2000; Doran et al., 2004). In recent years, however, optically stimulated luminescence (OSL) dating has been suggested as a technique that could be adapted to robotic in situ studies on Mars (Lepper and McKeever, 2000; McKeever et al., 2003).

OSL dating (Aitken, 1998) uses the principles of luminescence radiation dosimetry (Bøtter-Jensen et al., 2003) to generate absolute ages of aeolian and fluvial sediment deposition and has been used on Earth to date such deposits over the last several hundred thousand years of Earth's history (Roberts, 1997; Murray and Olley, 2002; Feathers, 2003). Recent advances have made it possible to produce an estimate of D_e from one aliquot (or subsample; ~ 5 mg) of quartz or polymineral fine-grains using the so-called single-aliquot regenerative-dose (SAR) procedure (Murray and Wintle, 2000; Banerjee et al., 2001), and further studies have indicated that the SAR procedure can also be applied to coarse-grain feldspars (Lamothe et al., 2001; Auclair et al., 2003; Blair et al., 2005b). By using a post-IR blue-stimulation procedure, the SAR procedure could even be used with polymineral coarse-grain samples to isolate mineral-specific OSL signals (i.e., a feldspar-dominated IR-stimulated signal and a quartz-dominated blue-stimulated

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signal, Blair, 2005). OSL dating of the martian surface will require robotic instruments in which only small amounts of regolith material will be used. Furthermore, without the ability for detailed mineral separation techniques, it is likely that only polymineral samples will be available for examination. Thus, these advances in the SAR techniques have made the application of OSL to in situ dating studies on Mars feasible.

Previous OSL studies have focused on the general luminescence properties of the martian soil simulant JSC Mars-1 (Lepper and McKeever, 2000; Banerjee et al., 2002a), and some of the engineering challenges to developing in situ OSL dating for Mars such as choosing the appropriate irradiation source, light stimulation unit, and light detection unit (McKeever et al., 2003; Blair et al., 2005a). As most luminescent materials on Mars are assumed to be some sort of feldspar, Blair et al. (2005b) concentrated on modifying the SAR procedure so that it can be used effectively with feldspathic materials. McKeever et al. (2006) have also looked at numerous methodological issues for performing OSL dating in the martian environment including the low ambient martian temperature, the unique mixture of minerals on Mars, the solar bleaching (i.e., zeroing of the OSL signal) of minerals under martian conditions, and the natural radiation dose rate at the martian surface due to the high flux of galactic cosmic rays (GCR) and solar energetic particles (SEP).

The current study evaluates the basic properties required for OSL dating for various martian regolith simulants and meteorites. The modified SAR procedure of Blair et al. (2005b) is used to study OSL properties of JSC Mars-1, two martian regolith simulants developed at Oklahoma State University (named OSU Mars-1 and OSU Mars-2, respectively) and several martian meteorites. The traps that give rise to the OSL signal are isolated; it is verified that the procedure corrects for any changes in OSL that may occur during the measurement procedure itself (i.e., sensitivity changes due to heating or optical stimulation); dose response curves are measured; and the suitability of the procedure for radiation dose estimation is evaluated. Estimates for maximum measurable doses and ages are also given.

2. Single-aliquot procedures

The introduction of single-aliquot procedures has revolutionized the field of OSL dating. In view of the fact that procedures such as SAR (Murray and Wintle, 2000) can produce depositional age estimates from one aliquot (∼ 5 mg of sample) as compared to earlier multiple-aliquot methods that required up to 80 aliquots, then the amount of required sample and the sample preparation time are greatly reduced. In addition, since all measurements are performed on the same aliquot, there is no need to normalize the luminescence output from different aliquots, thereby reducing uncertainty. Finally, single-aliquot procedures allow multiple equivalent doses to be easily produced thereby enabling more robust statistical analysis.

The SAR procedure first measures the OSL signal resulting from natural irradiation in the environment, and the equivalent dose (i.e., the radiation dose absorbed in nature) is inferred by interpolating the measured OSL signal from a series of "regeneration" or calibration doses. (The calibration doses are designed to "regenerate" the trapped electron distribution within the material caused by natural irradiation, and hence the term "regeneration dose".) Before measurement of any OSL signal, each aliquot is preheated at a specified temperature for a short time (e.g., 260 °C for 10 s) to remove electrons from traps that are unstable over the geological time scale of interest. However, during these repeated cycles of irradiation, preheating, and OSL measurement, the samples often experience sensitivity changes, that is, the changes in detected luminescence per unit absorbed dose. Sensitivity can be monitored by measuring the OSL response of the sample to a standard test dose. (The sensitivity measurement is normally done after measurement of the OSL due to the regeneration dose.) In the initial development of the SAR technique it was found that the majority of the sensitivity change takes place as a result of preheating (Murray and Wintle, 2000). Therefore, in order to prevent further sensitivity changes induced by the sensitivity measurement itself, it was suggested that the sample be heated to a lower temperature after the test dose than after the regeneration dose. Furthermore, the sample was immediately cooled rather than holding at that temperature. This has the effect of removing unstable components without inducing additional sensitivity changes. This is the so-called "cutheat", and Murray and Wintle (2000) suggested using 160 °C (for 0 s). Later studies suggested that the same cutheat cannot be used for all samples, and that preheat/cutheat combinations should be tested for each sample (Bailey, 2000). Finally, a sensitivity-corrected OSL signal is then obtained by dividing the OSL from the regeneration dose by OSL from the test dose.

The SAR procedure used in this paper is based on work with feldspar separated by Lamothe et al. (2001), Auclair et al. (2003), and Blair et al. (2005b). This body of research has suggested replacing the cutheat after the test dose with a preheat, equal to the preheat after the regeneration dose, in order for the sensitivity-correction procedure to work properly for these minerals. A summary of the SAR procedure used in this paper is given in Table 1.

Table 1
SAR procedure

1.	Regeneration radiation dose (D_i)
2.	Preheat at T_P° C[a] for 10 s
3.	Measure IRSL @ 60 °C (R_i)
4.	Measure OSL at 125 °C (R_i)
5.	Fixed test radiation dose (T_i)
6.	Preheat at T_P°C[a] for 10 s
7.	Measure IRSL @ 60 °C (T_i)
8.	Measure OSL at 125 °C (T_i)
9.	Repeat steps 1–8 for a range of regeneration doses including a repeat point and a 0 Gy dose
10.	Find sensitivity-corrected IRSL ($L_i = R_i/T_i$)
11.	Find sensitivity-corrected OSL ($L_i = R_i/T_i$)

This procedure has been modified from the SAR procedure for quartz (Murray and Wintle, 2000) so that it can be used with polymineral samples containing feldspars.
[a] T_P determined from experiment.

3. Materials and equipment

Characterization of the OSL properties in this study has been carried out for three different types of martian regolith simulants and four martian meteorites. The first regolith simulant studied is JSC Mars-1 which is soil from the Pu'u Nene volcano on Mauna Kea, Hawaii and was selected by Allen et al. (1998) as a regolith simulant based upon reflectance spectra. JSC Mars-1 is composed of altered volcanic ash and very closely matches the reflectance spectra of the bright regions of Mars with the exception of absorption bands for OH and H_2O. The regolith simulant consists of magnetic and non-magnetic fractions, both of which are made up of feldspar, magnetite, pyroxene, olivine, and volcanic glass. The magnetic fraction has a larger proportion of magnetite.

More recent data from the thermal emission spectrometer (TES) aboard Mars Global Surveyor (MGS) has suggested slightly different mixtures of minerals for analogs of martian regolith. Spectra from these instruments distinguish two different types of regolith on Mars, namely Type I (basaltic mineralogy) and Type II (andesitic mineralogy). Both types of regolith, according to the TES results, are composed of plagioclase feldspars, pyroxenes (primarily augite and diopside), and hematite, and the Type II material contains an abundance of obsidian or volcanic glass (Bandfield et al., 2000; Bandfield, 2002). Based upon these results, two mineral mixtures have been created in the OSL dating laboratory at OSU to be used as martian regolith simulants (Kalchgruber et al., 2006). The compositions of these mixtures are given in Table 2.

Most martian meteorites do not match well with the spectral characteristics of the martian surface and therefore may not be representative of martian soils (Bandfield, 2002). However, they are the only martian materials currently available and are therefore worthy of study. As such, the basic luminescence characteristics of four martian meteorites have been studied (kindly provided by Dr. Derek Sears of the University of Arkansas). The meteorites are ALH 77005,74, Shergotty (SH 400), Zagami, and EET 79001,74. Some of their basic luminescence properties have been previously studied (Banerjee et al., 2002b), and the TL results were found to be consistent with meteorites that contain feldspar in the low-temperature, ordered state. In this paper, the proposed procedure is tested in various ways on these martian meteorites and the results are described.

Table 2
Mineral abundances of two martian soil simulants, OSU Mars-1 and OSU Mars-2

Group/mineral	OSU Mars-1 (%)	OSU Mars-2 (%)
Quartz	0	0
K-feldspar	0	0
Plagioclase		
Bytownite	$21^{2/3}$	15
Andesine	$21^{2/3}$	15
Labradorite	$21^{2/3}$	15
Pyroxene		
Augite	15	5
Diopside	15	5
Obsidian	0	40
Hematite	5	5

All of the martian regolith simulants were sieved to obtain the 90–120 μm grain fraction, but, due to the small sample amounts, the martian meteorites were used as-received. (No attempt was made to determine the grain size of the latter samples.) All of the samples were affixed to stainless steel disks using silicone spray, and the experiments were conducted in a Risø TL/OSL DA-15 system (Bøtter-Jensen et al., 2000). They were irradiated by a $^{90}Sr/^{90}Y$ irradiation source delivering 0.112 Gy/s for calibrations. The samples were optically stimulated with blue light-emitting diodes (470 nmΔ20 nm) or with an infra-red diode laser (830 nmΔ10 nm). Light detection was accomplished via a photomultiplier tube (PMT) with bialkali photocathode (Thorn-EMI 9235QA), and the appropriate filter pack (containing U-340 filters transmitting from 300 to 380 nm) was placed in front of the PMT to limit the detection window.

4. Experimental procedures and results

4.1. Identification of optically active traps

The optically active traps (i.e., those traps from which electrons are released when exposed to light) for all of the materials were identified as follows: TL was first measured (heating to 500 °C) to remove any electrons from the traps. The samples were then given a 300 Gy (5000 Gy for JSC Mars-1) beta dose, stored for 600 s, and the TL was measured again (to 500 °C). The samples were then irradiated in the same way, bleached, and the TL was measured again. Note that appropriate pauses were added so that the TL was always measured 600 s after irradiation. This sequence was carried out three times using three different stimulation sequences—infra-red, blue, and post-IR blue stimulation sequences.[1]

The effect of bleaching by different wavelengths of light on the sample OSU Mars-1 is shown in Fig. 1(a) as an example. For JSC Mars-1, OSU Mars-1, and OSU Mars-2, infrared stimulation appears to affect mainly the lower stability traps— i.e., those causing the TL below 250 °C—with little change in the TL curve above this temperature. Blue and post-IR blue stimulation, on the other hand, both reduce the TL curve up to about 400 °C, although in each case the TL curve is unaffected for temperatures above 400 °C. It is important to note, however, that a significant TL signal remains above 100 °C for infrared stimulation and above 250 °C for blue stimulation after 300 s of stimulation. Yukihara et al. (2003) also found that a significant luminescence signal remains even after 1800 s of bleaching.

The effect of bleaching by different wavelengths on the TL of the martian meteorites was also studied, and the results for Shergotty are shown in Fig. 1(b). Three of the meteorites (ALH 77005,74, Shergotty, and EET 79001,170) show a large TL peak near 100 °C, while Zagami does not exhibit a clear TL

[1] Infra-red stimulation followed immediately by blue stimulation.

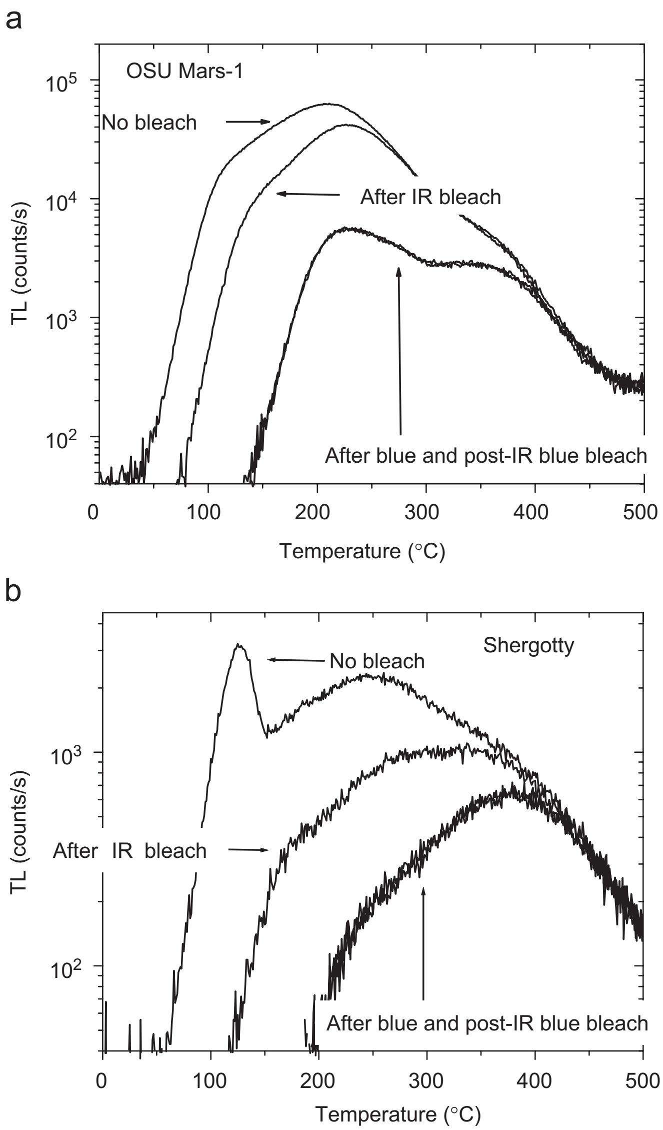

Fig. 1. The effect of bleaching on TL for (a) OSU Mars-1 and (b) Shergotty. The samples were given either 300 Gy dose, bleached with the indicated stimulation sources for 300 s, and TL was then measured to 500 °C.

peak at any temperature. All of the meteorites appear to show an almost continuous distribution of TL traps that is typical of feldspathic materials. Unlike the previous simulants studied (Blair, 2005), infrared, blue, and post-IR blue stimulation seem to affect mostly the same traps. Also, there is a significant residual TL signal after applying any of the bleaching methods.

4.2. Correcting for sensitivity changes

As noted above, the sensitivity correction procedure involves dividing the OSL from the regeneration dose by that from the test dose—i.e., the sensitivity-corrected signal L_i is given by the ratio of the regeneration signal R_i, divided by the test dose signal T_i ($L_i = R_i/T_i$). The index i represents the sequence of doses applied. ($i = 1$ means the first regeneration dose, etc.) The major underlying assumption for the sensitivity-correction procedure is that the change in the OSL signal measured after the test dose is an accurate measure of the sensitivity change exhibited by the OSL signal resulting from the regeneration dose. This assumption can be easily tested by performing repeated cycles of the SAR procedure with a fixed regeneration dose. If the test dose OSL signal (T_i) correctly measures the sensitivity changes of the regeneration dose OSL signal (R_i), the two signals will be directly proportional, i.e., plotting the regeneration dose OSL versus the test dose OSL will form a straight line that passes through the origin within uncertainty limits.

The above procedure was used to test the sensitivity-correction procedure for these samples. The SAR procedure as outlined in Table 1 was repeated seven times with a fixed regeneration dose of 40 Gy for the martian simulants and 100 Gy for the martian meteorites and using a test dose of 10 Gy for the martian simulants and 25 Gy for the martian meteorites. This procedure was followed for a range of preheats. Examples of the results are shown in Fig. 2 for OSU Mars-1 and Zagami. In all cases the plotted lines are linear, passing through the origin.

The martian regolith simulants showed little sensitivity change independent of the stimulation wavelength and for all preheats. As a result, the OSL intensities tend to cluster around one point in the plots of Fig. 2(a) and (b). In this case, sensitivity correction is not necessary, but the SAR procedure and sensitivity correction method can still be used. However, it should be noted that OSU Mars-1 and OSU Mars-2 did show some small OSL sensitivity changes when using low temperature preheats (160 and 200 °C) and infrared stimulation. Furthermore, the regeneration dose OSL signals showed sensitivity change while the test dose OSL signals did not (filled squares in Fig. 2(a) for OSU Mars-1, data not shown for OSU Mars-2). These trends were not as apparent in the blue-stimulated OSL data. Based upon these observations, it is concluded that the proposed procedure can be used for sensitivity-correction with the martian simulants, but low temperature preheats (below 200 °C) should not be used as sensitivity changes in the regeneration dose OSL and test dose OSL signals may not be proportional. It should also be noted that using high temperature preheats (greater than 280 °C) may not be suitable either as the OSL signals are greatly reduced by these high temperature preheats and small variations in the preheat temperature could lead to large errors in the OSL signals.

4.3. Dose response curves

One goal of the SAR procedure is to create a sensitivity-corrected dose response curve—i.e., one that shows the growth of the OSL as the regeneration dose is increased, undistorted by sensitivity changes. Uncorrected dose response curves often show nonlinearities such as supralinearity, sublinearity, or both. Supralinearity can be caused by an increase in the sensitivity (OSL signal per unit dose) of the sample, and the sensitivity-correction of the SAR procedure removes the supralinear region of the dose response curve (Chen and McKeever, 1997; Murray and Wintle, 2000; Banerjee et al., 2001).

Sensitivity-corrected ($L_i = R_i/T_i$) dose response curves are shown in Fig. 3 for OSU Mars-2 and for ALH 77005, 74. No supralinearity is present in the corrected dose response

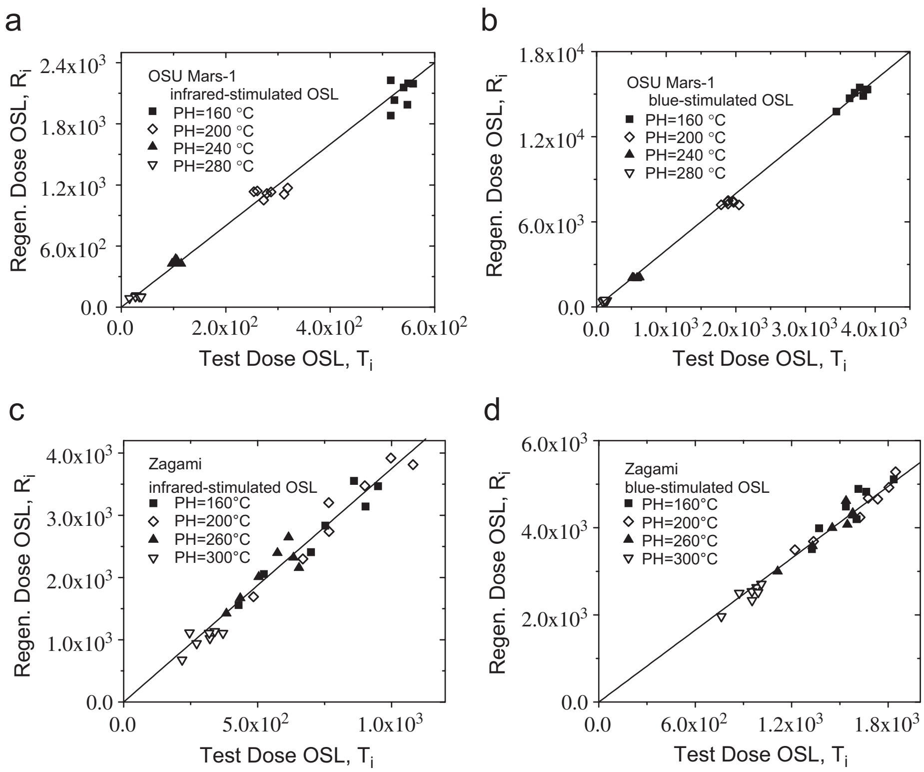

Fig. 2. Tests of the sensitivity-correction procedure for OSU Mars-1 and Zagami as labelled. The figures show data for ((a) and (c)) infrared-stimulated OSL as part of a post-IR blue stimulation sequence and ((b) and (d)) post-IR blue stimulated OSL. The straight lines represent a visual best fit to the data.

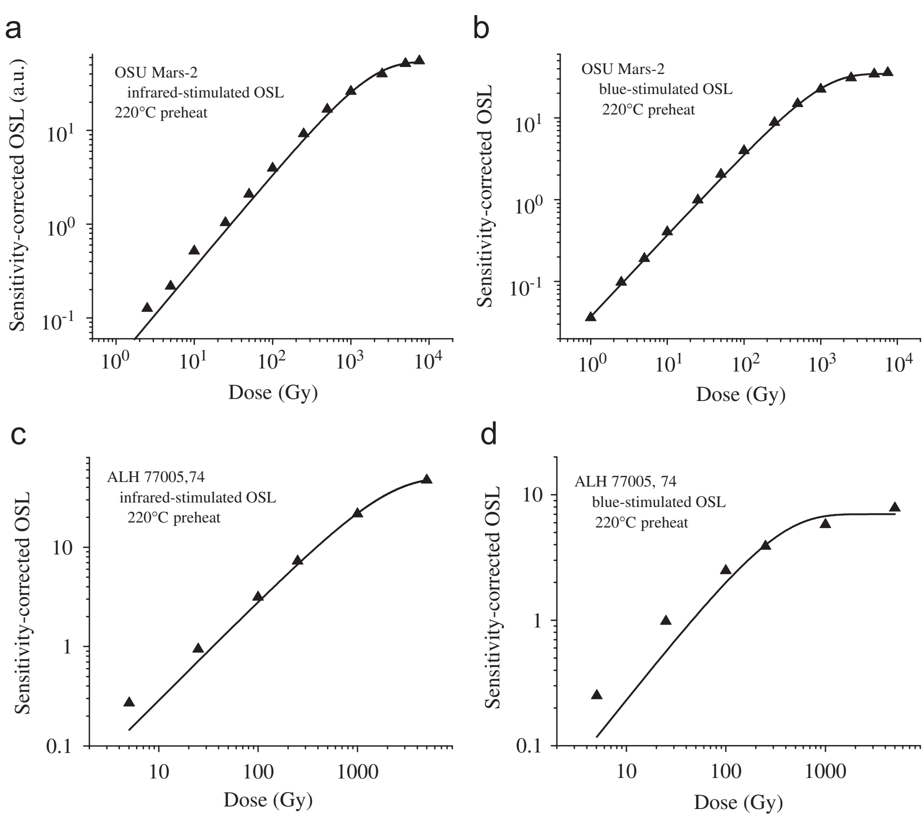

Fig. 3. Sensitivity-corrected dose–response curves for OSU Mars-2 and ALH 77005,74 as labelled. The figures show data for ((a) and (c)) infrared-stimulated OSL as part of a post-IR blue stimulation sequence and ((b) and (d)) post-IR blue stimulated OSL. Note the log-log scale. The solid lines are single-saturating exponential fits of the data.

Table 3
Results of dose recovery experiments for the infrared-stimulated OSL signal from a post-IR blue stimulation sequence

Sample	Infrared-stimulated OSL		
	Dose rec. ratio	Recycling ratio	Recuperation
JSC- Mars-1			
100 Gy (9)	1.01 ± 0.04	1.01 ± 0.10	0.11 ± 0.06
300 Gy(10)[a]	1.02 ± 0.03	1.03 ± 0.08	0.06 ± 0.01
OSU Mars-1			
15 Gy (10)	0.99 ± 0.04	1.07 ± 0.04	-0.01 ± 0.01
1000 Gy (5)	0.94 ± 0.13	1.02 ± 0.04	0.04 ± 0.03
OSU Mars-2			
15 Gy (10)	1.01 ± 0.04	1.04 ± 0.05	0.00 ± 0.01
1000 Gy (5)	0.93 ± 0.14	0.99 ± 0.03	0.03 ± 0.01
ALH 77005,74			
100 Gy (2)	0.98 ± 0.1	0.95 ± 0.01	0.08 ± 0.09
250 Gy (2)	1.02 ± 0.04	1.05 ± 0.01	0.19 ± 0.17
Shergotty			
100 Gy(2)	0.95 ± 0.54	0.95 ± 0.01	-0.04 ± 0.09
250 Gy (2)	0.99 ± 0.06	0.88 ± 0.02	0.06 ± 0.01
Zagami			
100 Gy (2)	0.85 ± 0.17	1.03 ± 0.03	0.07 ± 0.04
250 Gy (2)	1.07 ± 0.25	0.85 ± 0.30	0.10 ± 0.13
EET 79001,170			
100 Gy (2)	0.93 ± 0.32	0.97 ± 0.15	0.06 ± 0.01
250 Gy (1)[b]	1.07 ± 0.08	1.24	0.05

For each sample, doses were recovered in the linear (smaller dose) and non-linear (larger dose) portions of the dose response curve. The “dose rec. ratio” is the ratio of the recovered dose to the known dose, the “recycling ratio” is L_4/L_1 (the first and fourth regeneration doses are equal), and “recuperation” is L_5 resulting from a 0 Gy regeneration dose. All reported errors are the standard error unless otherwise noted. The number in parentheses is the number of aliquots used for that sample.
[a]Used local slope approximation rather than fitting dose response curve.
[b]Errors are based upon fitting errors.

Table 4
Results of dose recovery experiments for the blue-stimulated OSL signal from a post-IR blue stimulation sequence

Sample	Blue-stimulated OSL		
	Dose rec. ratio	Recycling ratio	Recuperation
JSC- Mars-1			
100 Gy (9)	0.97 ± 0.04	1.05 ± 0.03	0.06 ± 0.02
300 Gy(10)[a]	1.00 ± 0.02	1.01 ± 0.03	0.09 ± 0.01
OSU Mars-1			
15 Gy (10)	1.00 ± 0.02	1.04 ± 0.01	0.03 ± 0.02
1000 Gy (5)	0.92 ± 0.03	1.16 ± 0.02	0.07 ± 0.01
OSU Mars-2			
15 Gy (10)	0.97 ± 0.02	1.02 ± 0.02	0.01 ± 0.01
1000 Gy (5)	0.93 ± 0.02	1.11 ± 0.02	0.05 ± 0.01
ALH 77005,74			
100 Gy (2)	1.17 ± 0.49	0.99 ± 0.01	0.01 ± 0.01
250 Gy (2)	1.01 ± 0.10	1.07 ± 0.01	0.08 ± 0.01
Shergotty			
100 Gy (2)	1.09 ± 0.56	1.03 ± 0.03	0.02 ± 0.02
250 Gy (2)	0.89 ± 0.15	1.06 ± 0.33	0.06 ± 0.01
Zagami			
100 Gy (2)	1.01 ± 0.51	1.01 ± 0.01	0.02 ± 0.01
250 Gy (2)	0.86 ± 0.25	1.10 ± 0.09	0.10 ± 0.02
EET 79001,170			
100 Gy (2)	1.23 ± 0.15	0.97 ± 0.01	0.02 ± 0.01
250 Gy (1)[b]	0.89 ± 0.06	1.00	0.10

All terms are the same as those used in Table 4. The number in parentheses is the number of aliquots used for that sample.
[a]Used local slope approximation rather than fitting dose response curve.
[b]Errors are based upon fitting errors.

curves. JSC Mars-1 and the martian meteorites show a very small (if any) linear range, but OSU Mars-1 and OSU Mars-2 both display a long linear range followed by a quickly saturating portion of the sensitivity-corrected dose response curve.

4.4. Dose recovery experiments

Before a SAR-type procedure can be used to determine the radiation dose absorbed from the natural environment, the procedure needs to be tested by recovering a known laboratory dose. For this procedure, the aliquots to be tested are first bleached to remove the easily bleached component of the OSL signal. As mentioned earlier, bleaching (at least under the conditions used for this paper) does not remove all charge from the traps, but it does remove the majority of the OSL signal and mimics the effect of bleaching in nature under “good conditions” (e.g., aeolian transport in full sunlight). A known beta dose is then given to the aliquots in the laboratory, and this dose is treated as if it were the natural radiation dose. The SAR-type dose recovery process is then carried out to determine the laboratory (i.e., “natural”) absorbed dose, and the recovered equivalent dose is divided by the known dose to produce a dose recovery ratio. A dose recovery ratio of 1 indicates perfect determination of the delivered laboratory dose. In general practice, the dose recovery ratio should be between 0.95 and 1.05 for the known dose to be successfully recovered to within ±5%.

Dose recovery experiments were undertaken for all of the martian simulants and meteorites using known doses from both the linear and non-linear regions of the respective dose response curves, using the same preheats as those used to construct the respective dose response curves. Other parameters examined when assessing the efficacy of the SAR method include the average recycling ratio, and the average recuperation values. The recycling ratio is the ratio of the sensitivity-corrected OSL values of two regeneration doses that are equal (the fourth and first regeneration doses in these experiments), assesses the effectiveness of the sensitivity-correction procedure, and should be near 1.0 for a reliable SAR procedure. The recuperation ratio is the sensitivity-corrected OSL after a 0 Gy dose. It monitors the amount of charge that is thermally transferred from optically-inactive traps to optically-active traps, and should be a small percentage of the natural dose OSL (known dose OSL in this case) for a reliable SAR procedure. The dose recovery ratios, average recycling ratios, and average recuperation values for all of the dose recovery experiments, along with the dose recovered for each experiment, are given in Tables 3 and 4. The reported errors are the standard errors for the martian simulants (JSC Mars-1, OSU Mars-1, and OSU Mars-2), and the standard deviation for the martian meteorites unless otherwise noted.

For the martian simulants, doses from both the linear and non-linear portions of the dose response curves could be recovered with less than a 5% error with either IR or blue stimulation (from a post-IR blue stimulation sequence). In addition, the recycling ratios were generally close to 1.0 and the recuperation was a small percentage of the sensitivity-corrected OSL from the known dose. Dose recovery experiments with the martian meteorites could only be carried out on two aliquots due to the small amount of each meteorite available. Still, the known doses could generally be recovered with less than a 5% error.

5. Discussion

All of the samples showed bleaching characteristics typical of feldspathic samples in that no particular individual TL peak seems connected with the infrared or blue-stimulated OSL signals. This phenomenon in feldspars has been explained by OSL and TL accessing either a common recombination center or the same electron traps (Bøtter-Jensen et al., 1991; Duller and Bøtter-Jensen, 1993). However, other data (Blair et al., 2005b) suggests that infrared and blue stimulation access different traps, implying that the intensity of the TL curve is governed by the availability of common recombination centers rather than by the population of trapping centers.

The dose response curves for all of the samples were fitted with a single saturating exponential of the form:

$$L = a(1 - e^{-D/Dc}), \tag{1}$$

where L is the sensitivity-corrected luminescence, a is the asymptotic value of the sensitivity-corrected luminescence, D is the dose, and Dc is the characteristic dose. Following Banerjee et al. (2002a), the theoretical maximum estimable dose can be found from $D = 3.5 * Dc$, although in practice the maximum estimable dose is often $D = 2 * Dc$. Once the maximum estimable doses have been calculated, the maximum estimable ages could be calculated based upon an estimated martian surface dose rate of 50 mGy/year (McKeever et al., 2003). The results of these calculations are given in Table 5 and show a wide range of maximum depositional ages that could be obtained, assuming that these values are representative of those for the actual martian sediments. Generally, the maximum age that could be estimated from the infrared-stimulated OSL signal is larger than the maximum age that could be estimated from the blue-stimulated OSL signal for any given mineral mixture. For the infrared-stimulated OSL signal, the maximum estimable ages range from 67 ka (Shergotty meteorite) to 115 ka (ALH 77005,74 meteorite). For the blue-stimulated OSL signal, the maximum estimable age ranges from 7 ka (EET 79001,170 meteorite) to 64 ka (Zagami meteorite). As most samples have a minimum detectable dose of approximately 1 Gy, the minimum estimable age would be around 20 years. Thus, using these estimates as a guide, the time span of the geological framework that could be constructed for the martian surface morphology using OSL dating ranges from approximately 0.2 to 100 ka, but will be highly dependent upon the minerals that are present in the martian regolith.

Table 5
Calculations of the maximum estimable doses and ages from fitting of the dose response curves (see text)

Sample	Infrared-stimulated OSL		Blue-stimulated OSL	
	Max dose (Gy)	Max age (ka)	Max dose (Gy)	Max age (ka)
JSC Mars-1	5500	110	2100	42
OSU Mars-1	4400	88	2700	53
OSU Mars-2	4900	98	3100	62
ALH 77005,74	5700	114	230	16
Shergotty	3300	67	520	11
Zagami	4700	95	3200	64
EET 79001,170	4500	89	350	7

The calculations for both OSL signals from a post-IR blue stimulation sequence are presented. The maximum estimable age is based upon an average dose rate of 50 mGy/yr (McKeever et al., 2003).

6. Conclusions

This paper describes the characteristics of the basic luminescence properties of various martian simulants and meteorites. In particular, OSL tests were performed to determine if the polymineral SAR procedure of Table 1 could be used with these materials.

Even though the simulants and meteorites showed little or no sensitivity changes under repeated cycles of dose, preheating, and OSL measurement, the sensitivity correction of the proposed procedure is valid for both the regolith simulants and meteorites. The sensitivity correction method also produced dose response curves without any supralinearity. Statistical analysis of the sensitivity-corrected dose response curves indicate that ages as old as 115 ka might be produced from minerals similar to the tested materials. Taken together, these experiments reveal that the martian simulants and meteorites have the basic OSL characteristics necessary for a single-aliquot procedure.

Finally, known doses from both the linear and non-linear portions of the respective dose response curves could be accurately recovered using the proposed procedure, although the uncertainties for the martian meteorites were generally large. While this test is not definitive and is certainly not a substitute for dating samples with independent age controls, we conclude that the simulants and meteorites are good dosimetric materials.

The final test of any dose recovery procedure used in luminescence dating is estimating a natural dose. In the best scenario, the dose recovery procedure can be tested on samples that have independent age controls, i.e., the sediments or sediments from the same layer that have been dated by another chronological dating method such as radiocarbon dating. If this final test is passed, the dose recovery procedure can be used for routine OSL or TL dating procedures. However, the samples used in this study are not from depositional environments, and no attempt has been made to estimate natural doses from the samples.

References

Aitken, M.J., 1998. An Introduction to Optical Dating. Oxford University Press, Oxford, UK.

Albee, A.L., 2003. The unearthly landscapes of Mars. Sci. Am. 13, 34–44.

Allen, C.C., Jager, K.M., Morris, R.V., Lindstrom, D.J., Lockwood, J.P., 1998. JSC Mars-1: a martian soil simulant. Space 98, Proceedings of the American Society of Civil Engineers, pp. 469–476.

Armstrong, J.C., Leovy, C.B., 2005. Long term wind erosion on Mars. Icarus 176, 57–74.

Auclair, M., Lamothe, M., Huot, S., 2003. Measurement of anomalous fading for feldspar IRSL using SAR. Radiat. Meas. 37, 487–492.

Bailey, R.M., 2000. Circumventing possible inaccuracies of the single aliquot regeneration method for the optical dating of quartz. Radiat. Meas. 32, 833–840.

Bandfield, J.L., 2002. Global mineral distributions on Mars. J. Geophys. Res. 107 2001JE001510.

Bandfield, J.L., Hamvilton, V.E., Christensen, P.R., 2000. A global view of martian surface compositions from MGS-TES. Science 287, 1626–1630.

Banerjee, D., Murray, A.S., Bøtter-Jensen, L., Lang, A., 2001. Equivalent dose estimation using a single-aliquot of polymineral fine grains. Radiat. Meas. 33, 73–94.

Banerjee, D., Blair, M., Lepper, K., McKeever, S.W.S., 2002a. Optically stimulated luminescence signals of polymineral fine grains in the JSC Mars-1 soil simulant sample. Radiat. Prot. Dosim. 101, 321–326.

Banerjee, D., Blair, M., Sears, D.W.G., McKeever, S.W.S., 2002b. Dating martian meteorites: characterization of luminescence from a martian soil simulant and martian meteorites. Lunar. Planet. Sci XXXIII, 1561.

Blair, M.W., 2005. Development of optically stimulated luminescence dating techniques for application to terrestrial and martian studies. Unpublished Ph.D. Dissertation, Oklahoma State University.

Blair, M.W., Kalchgruber, R., Deo, S., McKeever, S.W.S., 2005a. Developing OSL geological dating techniques for use on future missions to Mars. Lunar Planet Sci XXXVI, 1317.

Blair, M.W., Yukihara, E.G., McKeever, S.W.S., 2005b. Experiences with single-aliquot procedures using coarse-grain feldspars. Radiat. Meas. 39, 361–374.

Bøtter-Jensen, L., Ditlefsen, C., Mejdahl, V., 1991. Combined OSL (infrared) and TL studies of feldspars. Nucl. Tracks Radiat. Meas. 18, 257–263.

Bøtter-Jensen, L., Bulur, E., Duller, G.A.T., Murray, A.S., 2000. Advances in luminescence instrument systems. Radiat. Meas. 32, 523–528.

Bøtter-Jensen, L., Mckeever, S.W.S., Wintle, A.G., 2003. Optically Stimulated Luminescence Dosimetry. Elsevier, Amsterdam.

Chen, R., McKeever, S.W.S., 1997. Theory of Thermoluminescence and Related Phenomena. World Scientific, Singapore.

Clifford, S.M., et al., 2000. The state a future of Mars polar science and exploration. Icarus 144, 210–242.

Doran, P.T., et al., 2004. Mars chronology: assessing techniques for quantifying surficial processes. Earth-Sci. Rev. 67, 313–333.

Duller, G.A.T., Bøtter-Jensen, L., 1993. Luminescence from potassium feldspars stimulated by infrared and green light. Radiat. Prot. Dosim. 47, 683–688.

Edgett, K.S., Malin, M.C., 2000. New views of Mars eolian activity, materials, and surface properties: three vignettes from the Mars Global Surveyor Mars Orbiter Camera. J. Geophys. Res. 105, 1623–1650.

Feathers, J.K., 2003. Use of luminescence dating in archaeology. Meas. Sci. Technol. 14, 1493–1509.

Greeley, R., 1992. Saltation impact as a means of raising dust on Mars. Planet. Space Sci. 50, 151–155.

Herkenhoff, H.E., et al., 2004. Evidence from Opportunity's microscopic imager for water on Meridiani Planum. Science 306, 1727–1730.

Kalchgruber, R., Blair, M.W., McKeever, S.W.S., 2006. Dose recovery with plagioclase and pyroxene samples as surrogates for martian surface sediments. Radiat. Meas. 41, 762–767.

Knauth, L.P., Burt, D.M., Wohletz, K.H., 2005. Impact origin of sediments at the Opportunity landing site. Nature 438, 1123–1128.

Lamothe, M., Duller, G.A.T., Huot, S., Wintle, A.G., 2001. Measuring a laboratory radiation dose in feldspar using SAR. First North American Luminescence Dating Workshop, Tulsa, OK.

Lepper, K., McKeever, S.W.S., 2000. Characterization of fundamental luminescence properties of the Mars soil simulant JSC Mars-1 and their relevance to absolute dating of martian sediments. Icarus 144, 295–301.

McKeever, S.W.S., et al., 2003. Concepts and approaches to in situ luminescence dating of martian sediments. Radiat. Meas. 37, 527–534.

McKeever, S.W.S., Kalchgruber, R., Blair, M.W., Deo, S., 2006. Development of methods for in-situ dating of Martian sediments. Radiat. Meas. 41, 750–754.

Murray, A.S., Olley, J.M., 2002. Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz: a status review. Geochronometria 21, 1–16.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiat. Meas. 32, 57–73.

Roberts, R.G., 1997. Luminescence dating in archaeology: from origins to optical. Radiat. Meas. 27, 819–892.

Yukihara, E.G., Whitley, V.H., Blair, M.W., McKeever, S.W.S., 2003. Preliminary investigation of TL and OSL properties of individual emission bands in feldspars. Second North American Luminescence Dating Workshop, Albuquerque, NM.